

A Simulation of Radio Frequency Plasmas Sustained in Electropositive Gas

L. SETTAOUTI and A. SETTAOUTI

Electrotechnic Department, University of Sciences and Technology, Oran EL-M'NAOUAR, Algeria.

Abstract

Plasma enhanced etching and deposition is crucial in microelectronic device fabrication and in materials processing in general. In this process, low pressure electric gas discharges (plasmas) are used to dissociate a feedstock gas into radicals which react to etch the substrate or to deposit a solid film. To attain better results in these application fields, a quantitative understanding of the glow discharge is required. Computational modeling is a key tool for studying collisional plasma discharges. The Monte Carlo simulation have become increasingly important as a simulation tool. In this work, we present some detailed properties of radio frequency (rf) plasmas obtained by Monte Carlo simulation code, in an electropositive gas

1. INTRODUCTION

Glow discharges are being used in many fields of application. They serve extensively as plasma processing devices in microelectronics, e. g., ion etching, thin film deposition, and plasma surfaces treating, and they also find application as atomization - excitation - ionization sources in analytical chemistry. A wide range of parameter can be chosen to operate the plasma processes. By parameters here we mean those quantities that can be varied by changing not only the position of some external quantities (for example, pressure, current or voltage applied, and frequency), but also other quantities that cannot be easily varied (such as electrode spacing) [1-4].

In the past statistically designed experiments have been used, together with simple reaction diffusion and electrical analog models to design industrial processes, and to study the phenomena within the plasma. All these efforts try to shed light a posteriori to the plasma dynamics are available, similar to the ones used for solid state devices. The lack of such tools for simulation of the plasma dynamics is partly due to the synergy of the many phenomena that simultaneously take place and complicate the plasma process [5-9].

Plasma process modeling can be broken into modules which describe the plasma physics, the transport of gaseous species and the gas and surface chemistry. At a later stage the modules can be merged by including the interactions among them. And the fluctuations in rf plasmas make experimental investigation of their properties in space and time difficult. Due to the importance of glow discharge process, there has been an increased effort to understand and model them [5-9].

In this work, we present some detailed properties of rf plasmas obtained by Monte Carlo simulation code, in an electropositive gas.

2. SIMULATION MODEL

The electron transport in a gas under the influence of an electric field E can be simulated with the help of a Monte Carlo method. [10-12] Every electron, during its transit in the gas, performs a succession of free flights punctuated by elastic or inelastic collisions with molecules of gas defined by collision cross sections. During the successive collisions for every electron, certain information (velocity, position, etc.) is stored in order to calculate, from appropriate sampling methods, transport coefficients and macroscopic coefficients.

A simple group of electrons, typically 100 500, is randomly seeded between the electrode plates. The initial distributions of simulation particles are assumed to be Maxwellian distribution of 5 eV for electrons. The three dimensional motion of electrons between two successive collisions under the electric field is solved numerically with use of Euler method [19,20]. Electron flight time between two successive collisions is determined by the electron collision cross section with Ar neutral particles. The scattering after all collisions is assumed to be isotropic. The secondary electron emission coefficient due to electrons flowing to the two electrodes is assumed to be zero. The distribution of the electric field is calculated from the solution of the one dimensional Poisson's equation with the use of the electron and ion densities at the end of each time step. Electron trajectories are computed using Monte Carlo method for an rf parallel plate discharge in an electropositive gas (Ar) while oscillating the applied electric field providing a time and spatially dependent electric

field, many rf cycles are computed. The electrode system is assumed to consist of parallel plates with a diameter that is larger than the electrode separation. The probability of collision and the nature of collision are simulated by comparison with computer generated random numbers. The total number of electrons in the gap increases over many orders of magnitude, hence scaling is necessary to limit the number of simulation particles. When, the total number of simulation particles, exceeds the maximum allowable number of simulation particles, which is specified in the program input data, a statistical subroutine is introduced to choose a new group of larger particles to represent the old larger group of smaller particles. The subroutine contains a weighing of velocity distribution of the old group, so that the new group is equivalent in phase space to the old group.

3. RESULTS AND DISCUSSION

In this paper we present typical results of numerical simulations using a Monte Carlo method of rf plasmas sustained by an rf external source of 13.56 MHz and 200 V, in an argon model gas. The electrode system is assumed to consist of parallel plates with a diameter that is larger than the electrode separation. Electrode separation and gas pressure used are 2 cm and 0.6 Torr, respectively. The electron collision cross sections set of Ar employed is that referred in [13-16].

The electric field in the first cycle oscillates with a period corresponding to the rf cycle. In the Fig. 1. shows that the mean electron energy in the first rf cycle is maximum when the electric field for this cycle is maximum, and minimum where the electric field is minimum. And is almost spatially constant, and oscillates with the rf external field.

It is seen from Fig. 2. that the electron density is low at the beginning of the avalanche growth, as time increases, the enhancement becomes greater. And oscillate with the change in the direction of the electric field.

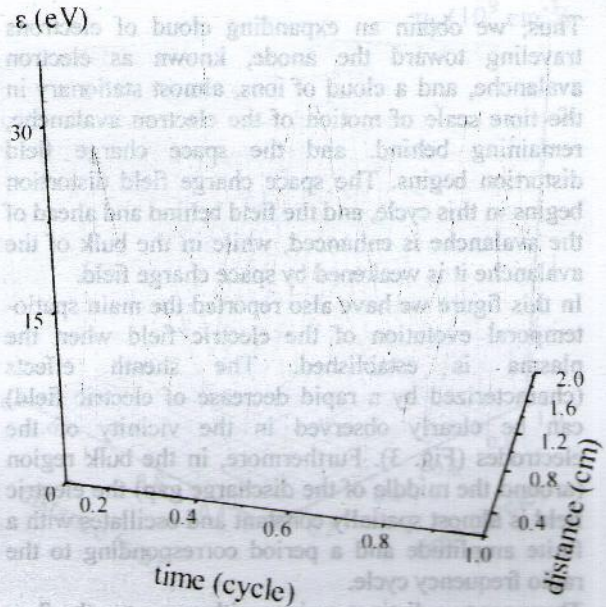


Fig. 1. Temporal and spatial variations of the mean energy of electrons for the first rf cycle.

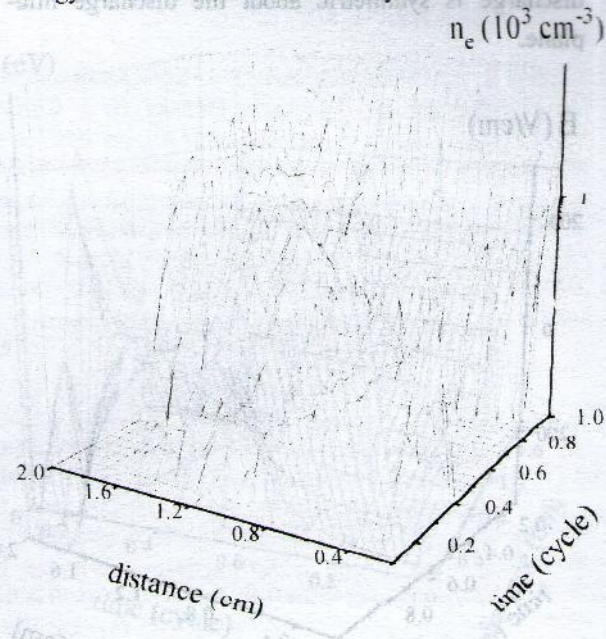


Fig. 2. Temporal and spatial variations of the electron density for the first rf cycle.

Fig. 3. shows, the spatial and temporal evolution of the electric field during the second radio frequency cycle. When the applied electric field is sufficiently large, the electron accelerates to high enough kinetic energies that inelastic collisions between the electron and the background gas occur. As the electron proceeds from the cathode to the anode, driven by the applied electric field. It undergoes many ionizing collisions in each of which an ion and another electron are formed.

Thus, we obtain an expanding cloud of electrons traveling toward the anode, known as electron avalanche, and a cloud of ions, almost stationary in the time scale of motion of the electron avalanche, remaining behind. and the space charge field distortion begins. The space charge field distortion begins in this cycle, and the field behind and ahead of the avalanche is enhanced, while in the bulk of the avalanche it is weakened by space charge field.

In this figure we have also reported the main spatio-temporal evolution of the electric field when the plasma is established. The sheath effects (characterized by a rapid decrease of electric field) can be clearly observed in the vicinity of the electrodes (Fig. 3). Furthermore, in the bulk region (around the middle of the discharge gap) the electric field is almost spatially constant and oscillates with a finite amplitude and a period corresponding to the radio frequency cycle.

There are two distinct regions with respect to the flow of electron energy in a parallel plate rf discharge, the bulk plasma and the sheaths. The electric field for the discharge is symmetric about the discharge mid-plane.

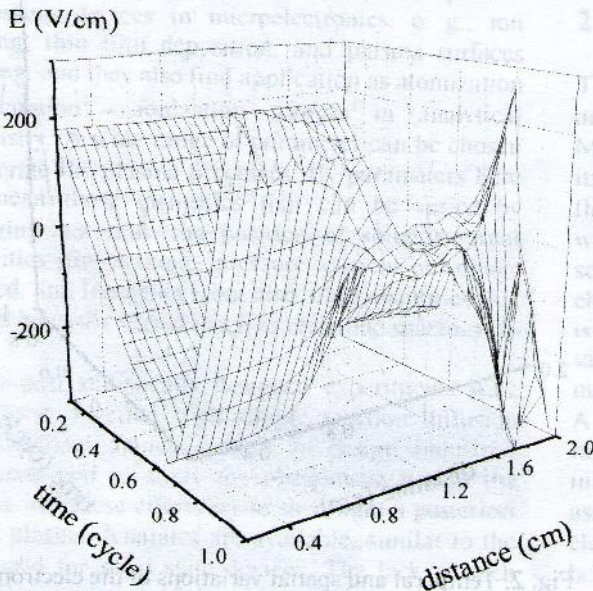


Fig. 3. Temporal and spatial variations of the electric field for the second cycle.

We also see from Fig. 3, that the electric field in the sheath regions, adjacent to the electrodes, oscillates with significant amplitude with period corresponding to that of rf cycle. Most of radio frequency external electric field is absorbed in the sheath regions. The electric field in the sheath changes almost linearly from both electrodes to the edge region of the bulk plasma (Fig. 3).

As the cycle advances, electrons are pushed out of the right sheath and into the left one. The movement of electrons causes a modulation of sheath width. The sheaths are quite wide causing the discharge to behave capacitively. The apparent sheath thickness is 0.3 cm. The central bulk plasma is characterized by a weak electric field (few V/cm).

The calculated electric field and sheath thickness are shown in Fig. 3 and compared with the measured values [17,18], the agreement between our results and those referred to above is very good.

Electrons are contained in the plasma in part by the space charge fields. Depending on the phase of the applied potential, electrons move toward either electrode. Their movement affects the local field causing electrons to pile in the bulk sheath interface. The charged particle density profiles for Ar are shown in Fig. 4.1, Fig. 4.2, Fig. 4.3 and Fig. 4.4.

Thus peaks appear in the electron density, which are shown in Fig. 4.1 as a function of position and time, and in the Fig. 4.2 as a function of the position.

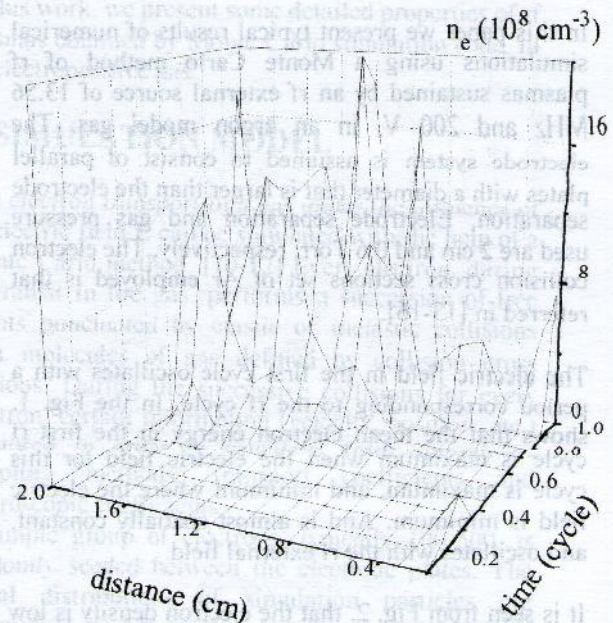


Fig. 4.1. Temporal and spatial variations of the electron density for one rf cycle.

Fig. 4.4. shows the temporal and spatial variations of the positive ion density due to the ionization, the ion density is not modulated significantly in time. From the Fig. 4.3 we see the positive ion density as a function of position,. The positive ion density form an envelope around electrons, which move in and out of the sheath region.

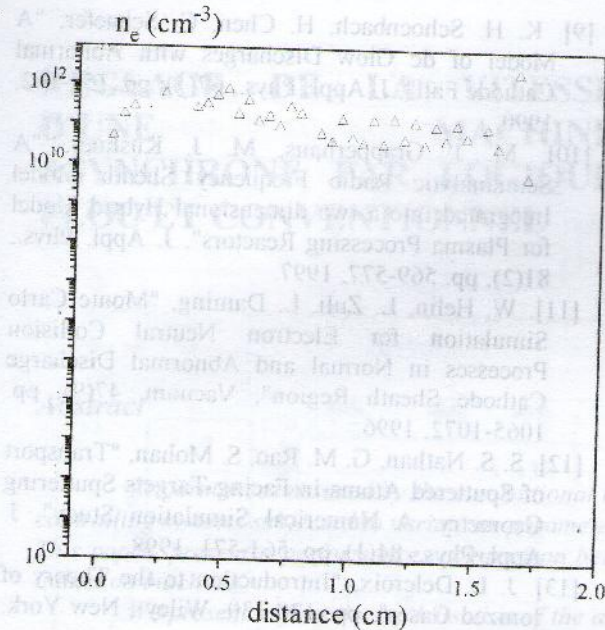


Fig. 4.2 electron density in Ar discharge as a function of position.

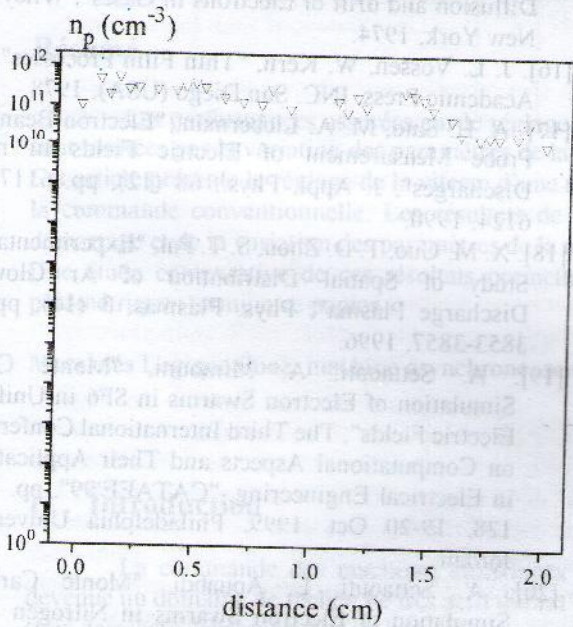


Fig. 4.3 Positive ion density in Ar discharge as a function of position.

The agreement between, the calculated charged particle density compared with the measured values [17,18] is good.

In Fig. 5. the spatiotemporal profiles of the electron mean energy show the different natures of the three regions in the discharge. The electron mean energy is nearly constant and uniform through the plasma bulk region and the relatively large modulations take place in sheath regions.

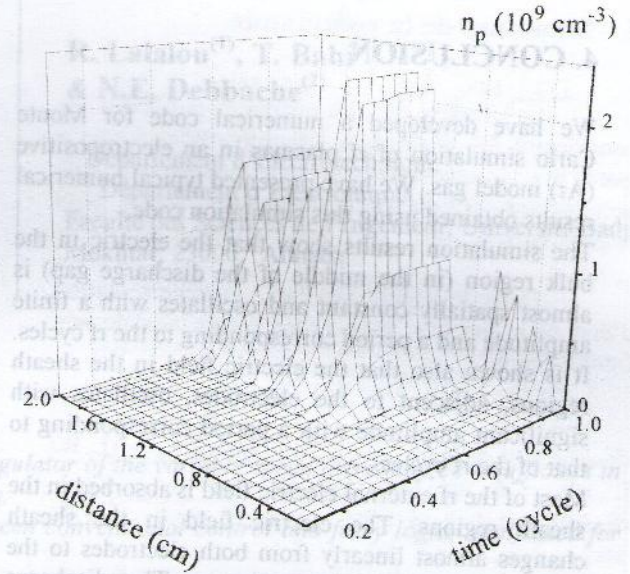


Fig. 4.4. Temporal and spatial variations of the positive ion density for one rf cycle.

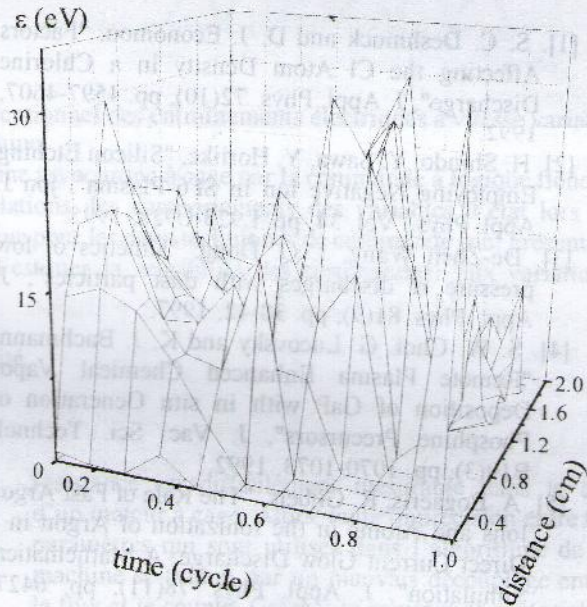


Fig. 5. Temporal and spatial variations of the mean energy of electrons for one rf cycle.

The electric field is maximum in the sheath and minimum in the bulk region. Such a maximum in the electric field in the sheath regions create a maximum in the average electron energy shown in Fig. 5. (here the secondary electron emission was assumed to be zero).

Indeed the maximum in the electric field are close to the maximum in energy, but not exactly at the same position in space or time because we do not assume local equilibrium with the field. And is almost constant in time and space in the bulk region, when the electric field is minimum.

4. CONCLUSION

We have developed a numerical code for Monte Carlo simulation of rf plasmas in an electropositive (Ar) model gas. We have presented typical numerical results obtained using this simulation code.

The simulation results show that the electric in the bulk region (in the middle of the discharge gap) is almost spatially constant and oscillates with a finite amplitude and a period corresponding to the rf cycles. It is shown also that the electric field in the sheath regions, adjacent to the electrodes, oscillates with significant amplitude with a period corresponding to that of the rf cycles.

Most of the rf external electric field is absorbed in the sheath regions. The electric field in the sheath changes almost linearly from both electrodes to the edge region of the bulk plasma. The discharge parameters are symmetric about the discharge mid-plane.

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